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# A complete transition to clean household energy can save one–quarter of the healthy life lost to particulate matter pollution exposure in India

# A complete transition to clean household energy can save one–quarter of the healthy life lost to particulate matter pollution exposure in India

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## Keywords

Particulate matter, ambient air pollution, household air pollution, India, solid fuel intervention, health impact assessment, disease burden

## Abstract

Exposure to fine particulate matter ($PM_{2.5}$) is a leading contributor to the disease burden in India, largely due to widespread household solid fuel use. The transition from solid to clean fuels in households has the potential to substantially improve public health. India has implemented large initiatives to promote clean fuel access, but how these initiatives will reduce $PM_{2.5}$ exposure and the associated health benefits have not yet been established. We quantified the impacts of a transition of household energy from solid fuel use to liquefied petroleum gas (LPG) on public health in India from ambient and household $PM_{2.5}$ exposure. We estimate that the transition to LPG would reduce ambient $PM_{2.5}$ concentrations by 25%. Reduced exposure to total $PM_{2.5}$ results in a 29% reduction in the loss of healthy life, preventing 348,000 (95% uncertainty interval, UI: 284,000–373,000) premature mortalities every year. Achieving these benefits requires a complete transition to LPG. If access to LPG is restricted to within 15 km of urban centres, then the health benefits of the clean fuel transition are reduced by 50%. If half of original solid fuel users continue to use solid fuels in addition to LPG, then the health benefits of the clean fuel transition are reduced by 75%. As the exposure–outcome associations are non–linear and the joint effects of ambient and household $PM_{2.5}$ are proportional, it is critical for air pollution studies of residential emissions to consider the disease burden attributed to total $PM_{2.5}$ exposure, and not only the portion attributed to either ambient or household $PM_{2.5}$ exposure. This work shows that a transition to clean household energy can

substantially improve public health in India, however, these large public health benefits are dependent on the complete transition to clean fuels for all.

# 1. Introduction

Fine particulate matter ($PM_{2.5}$) exposure is a leading contributor to disease burden in India, associated with 8% (95% uncertainty interval, UI: 7–9) of healthy life lost (disability–adjusted life years, DALYs) (India State-Level Disease Burden Initiative Air Pollution Collaborators 2019). The majority of the air pollution disease burden in India is from ambient $PM_{2.5}$ ($APM_{2.5}$) exposure (55% of DALYs), with a substantial contribution from household $PM_{2.5}$ ($HPM_{2.5}$) exposure (41% of DALYs) (GBD 2017 Risk Factor Collaborators 2018). Household solid fuel use is also the dominant source (22–56%) of $APM_{2.5}$ concentrations in India (Chowdhury et al 2019a, Conibear et al 2018, Lelieveld et al 2015, Guo et al 2018, GBD MAPS Working Group 2018, Reddington et al 2019, Butt et al 2016, Gao et al 2018, Silva et al 2016, Karagulian et al 2017, Chafe et al 2014, Upadhyay et al 2018). The implication is that more than half of the loss of healthy life associated with air pollution exposure in India is attributed to household solid fuel use (GBD 2017 Risk Factor Collaborators 2018).

Incomplete combustion of solid fuels leads to substantial emissions of toxic air pollutants (Naeher et al 2007, Adetona et al 2016, Gordon et al 2014). Epidemiological studies have found that a transition from solid to clean fuels in Indian homes can improve respiratory and cardiovascular outcomes (Hystad et al 2019, Lewis et al 2017, Sukhsohale et al 2013, Balmes 2019, Arlington et al 2019). Up until 2015, 700 million people across India primarily used solid fuels, a number that has not changed for several decades (Smith 2017a). Residential solid fuel use includes a wide range of fuels including firewood, charcoal and animal dung. Past solid fuel interventions in India, such as the National Programme on Improved Chulhas and the National Biomass Cookstoves Initiative, focused on clean and efficient combustion of biomass in "improved cookstoves" (Smith and Sagar 2014, Venkataraman et al 2010). However, the penetration of these stoves remained lower than aimed (Hanbar and Karve 2002, Smith 1993, Government of India 2011) and the emission reductions of these improved cookstoves are more limited in the field than laboratory studies suggest (Pope et al 2017, Aung et al 2016, Grieshop et al 2017, Sambandam et al 2015).

Since 2015, three programmes have promoted liquefied petroleum gas (LPG) access to poor households (Mittal et al 2017). The Pratyaksh Hanstantrit Labh scheme directly pays fuel subsidies into individuals bank accounts (Ministry of Petroleum and Natural Gas 2018c, Smith 2017b). The Pradhan Mantri Ujjwala Yojana scheme aims to provide connections to distributors and enable access to subsidised LPG to 80 million poor households by 2020 (Ministry of Petroleum and Natural Gas 2018a, Dabadge et al 2018, Ministry of Petroleum and Natural Gas 2018b, Goldemberg et al 2018, Ministry of Petroleum and Natural Gas 2019). The "Give it up" scheme aims to persuade middle–class households to give up their fuel subsidies which are then redirected to poor households (Government of India 2018). The combined aims of these programmes are to provide clean cooking to 80% of all households by 2019, and 90% by the early 2020s (Goldemberg et al 2018). The Ujjwala scheme aimed to provide LPG access to 80 million poor households was achieved ahead of schedule in September 2019. The Ujjwala scheme is now in hiatus with a updated version in development (Harish and Smith 2019). Following these programmes, and the continued growth of LPG use for the middle–class without subsidies, the number of solid fuel users is likely to decline.

The transition to clean household energy has the potential to substantially improve public health in India, dependent on access and usage (Tripathi and Sagar 2019, Kar et al 2019, Pattanayak et al 2019, Harish and Smith 2019, Gould and Urpelainen 2018). Access is essential and these LPG programmes have overcome various access issues, such as supply chain distribution problems, connections, and financial access for many. Access alone is not sufficient for a complete transition to clean household energy, as continued usage is required replacing solid fuel use. Usage issues, such as continual affordability, awareness, and stacking with solid fuels, can be common after access is achieved, potentially offsetting public health benefits (Rehfuess et al 2014, Lewis and Pattanayak 2012, Clark et al 2017, Pillarisetti et al 2014, Lozier et al 2016). The potential of these LPG programmes to reduce total $PM_{2.5}$ ($TPM_{2.5}$, i.e. $APM_{2.5}$ and $HPM_{2.5}$) exposure and the associated disease burden have not yet been established. We used a regional chemical transport model with a novel residential emission inventory to explore how hypothetical transitions to clean household energy could change $TPM_{2.5}$ exposure and the loss of healthy life under different access and usage scenarios. We do not attempt to evaluate the impact of specific ongoing clean household energy programmes.

## 2. Methods

### 2.1. Model description

Simulations were conducted using the Weather Research and Forecasting model online–coupled with Chemistry (WRF–Chem) version 3.7.1 (Grell et al 2005), incorporating various model improvements, including updated anthropogenic emissions, aqueous chemistry, and a more complex secondary organic aerosol scheme. Detailed information on the model setup is provided in Supplementary Table 1 and the Supplementary Methods. Simulations were for the year of 2016 with one month spin–up. The model domain covered South Asia at 30 km (0.3°) horizontal resolution.

Anthropogenic emissions of black carbon (BC), organic matter (OM), non–methane volatile organic compounds (NMVOC), nitrogen oxides ($NO_X$), other $PM_{2.5}$, and sulphur dioxide ($SO_2$) for residential biomass (wood, dung, and crop residues for cooking, space heating, and water heating), residential LPG (including biogas), residential kerosene, and residential lighting are for 2010 from a new residential inventory for India (Lam et al 2019). These emissions were produced at 1 km spatial resolution based on village surveys of energy services required, then aggregated to 0.25° × 0.25° horizontal resolution. Emission factors for the residential sector were completely reassessed to include field–measured emission factors that have recently become available. Residential kerosene use is diminishing in India without the need for further incentives.

Anthropogenic emissions of BC, organic carbon (OC), NMVOC, $NO_X$, other $PM_{2.5}$, and $SO_2$ for open burning, power plant coal (thermal), industrial coal (heavy and light), brick production, transportation (on–road gasoline/compressed natural gas, on–road diesel, and railways), distributed diesel (agricultural tractors, agricultural pumps, and diesel generator sets), and other sources (informal industry, trash burning, and urban fugitive dust) were taken from Venkataraman et al (2018) as used by the Global Burden of Disease from Major Air Pollution Sources study for 2015 at 0.25° × 0.25° horizontal resolution (GBD MAPS Working Group 2018, Venkataraman et al 2018). Anthropogenic emissions of carbon monoxide (CO), ammonia ($NH_3$), acetylene ($C_2H_2$), and methane ($CH_4$) were from the Emission Database for Global Atmospheric Research with Task Force on Hemispheric Transport of Air Pollution version 2.2 for 2010 at 0.1° × 0.1° horizontal resolution (Janssens–Maenhout et al 2015).

### 2.2. Household energy scenarios

To understand the impacts of interventions to replace solid fuel use with LPG, this study completed annual simulations using five different emission scenarios (Table 1). Household energy scenarios are split by access and usage issues, relative to a complete transition.

**Table 1:** Household energy scenarios (Lam et al 2019).

| Scenario | Description |
|---|---|
| **BASELINE** | A counterfactual scenario representative of 2015 before these LPG programmes begun. Household solid fuel use based on energy use characteristics with emissions informed by village and town data in the 2011 census and other sources (Government of India 2011, Lam et al 2019). |
| **ALLLPG** | Energy services currently met with biomass were completely replaced by fuels with LPG–equivalent energy and emission characteristics for cooking, water heating, space heating services, and zero–emission electric sources for residential lighting. The residential emissions here do not account for LPG leakages at point of use or in the delivery system. This scenario reflects the theoretical potential of a complete transition to clean household energy, assuming complete coverage and adoption. We do not attempt to simulate specific LPG programmes in India. We note that there are currently no clean–fuel interventions for space, water, and fodder heating. |
| **URB15** | An access scenario, where energy transition characteristics of ALLLPG but only for households within 15 km from urban areas. This scenario considered that programmes have limited effectiveness outside of urban areas, driven by a variety of factors, including plausible access to commercially distributed fuels. |
| **STATE50** | An access scenario, where emission reduction in URB15 were applied evenly across each state. Anthropogenic emission totals were the same within the URB15 and STATE50 scenarios, but the spatial distributions were different. |
| **EMIS50** | A usage scenario, where all households were assumed to have access to LPG (as in ALLLPG) but households continued to use solid fuels 50% of the time (stacking) in addition to using LPG. Residential emissions were estimated as 50% of residential emissions from the BASELINE scenario added to the residential emissions from the ALLLPG scenario. The extent of stove stacking was a conservative approximation of the recently updated CEEW dataset of energy access across 6 Indian states (Jain et al 2018). |

Figure 1 shows the annual anthropogenic emission totals from these scenarios. In the BASELINE scenario, residential biomass makes a substantial contribution to anthropogenic OC and NMVOC emissions. Power plant and industrial coal use dominate anthropogenic emissions of other chemical components of $PM_{2.5}$, $SO_2$, and $NO_X$. Anthropogenic dust, open burning, and trash burning contribute strongly to anthropogenic $PM_{2.5}$ emissions. Transportation and distributed diesel contribute heavily to anthropogenic $NO_X$ and NMVOC emissions. Under the ALLLPG scenario, total BC emissions are reduced by 47%, and OC emissions by 77%, contributing to a 44% reduction in total primary $PM_{2.5}$ emissions relative to the BASELINE. There are also substantial reductions in NMVOC (28%) emissions, while $SO_2$ and $NO_X$ emissions are reduced by less than 2%. Applying the spatial constraint to the intervention as in URB15, resulted in half the emission reduction that was achieved in ALLLPG. The stove stacking scenario in EMIS50 resulted in similar total emission reductions to URB15, but with different spatial patterns.

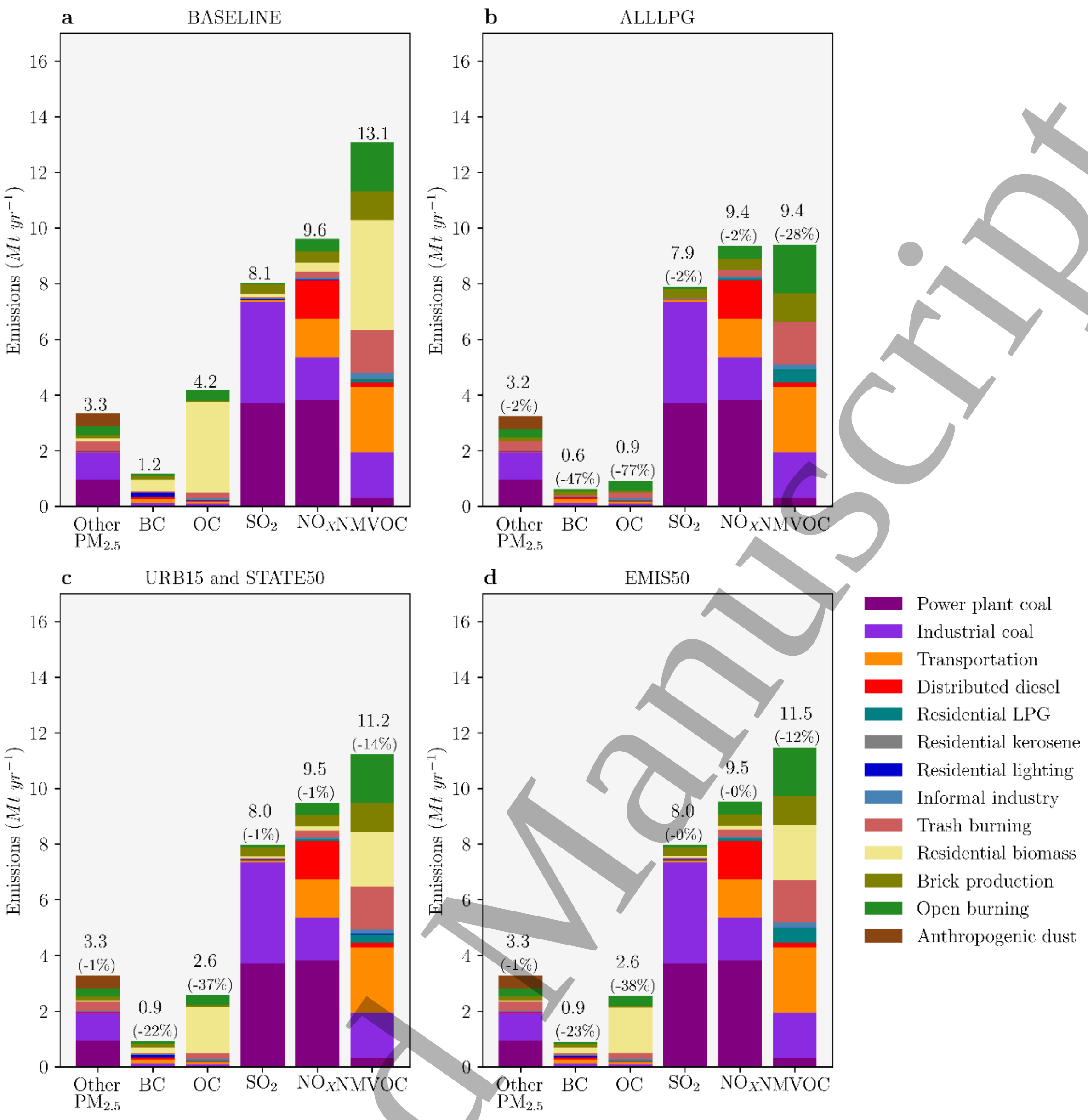


**Figure 1:** Anthropogenic emission totals for other fine particulate matter ($PM_{2.5}$) excluding black carbon (BC) and organic carbon (OC), then individual totals for BC, OC, sulphur dioxide ($SO_2$), nitrogen oxides ($NO_X$), and non–methane volatile organic compounds (NMVOC), from all sectors. Subplots (a–d) show the emission scenarios used in this study based on Global Burden of Disease from Major Air Pollution Sources emissions (GBD MAPS Working Group 2018, Venkataraman et al 2018) with the residential emissions from (Lam et al 2019) for the BASELINE, ALLLPG, URB15 and STATE50, and EMIS50 scenarios, respectively. Emission totals (Mt) per pollutant shown above corresponding bar, with the percentage reduction relative to the BASELINE for subplots (b–d).

### 2.3. Model evaluation

Model evaluation was conducted using measurements obtained from OpenAQ (OpenAQ 2019). Following Manning et al (2018), sites were accepted for evaluation when there was more than 16 hours of data per day, more than 50 days of data, and when hourly–mean $PM_{2.5}$ concentrations were greater than 5 μg $m^{-3}$ (93% acceptance). Measurements were aggregated to annual–means. There were 34 OpenAQ measurement sites in India for 2016 that passed this criteria, and this study compares the same days in the model as there are data in the measurements. The normalised mean bias factor (NMBF) and the normalised mean absolute error factor (NMAEF) were used to evaluate the model (Yu et al 2006). The measurements from OpenAQ were primarily collected from the Central Pollution Control Board (Ministry of Environment and Forests 2018). To increase the sample size of measurement sites for evaluation, these were combined with the World Health Organization Global Ambient Air Quality Database for measured annual–mean $PM_{2.5}$ concentrations in 2016 (World Health Organization 2018).

The model captures the spatial variation and magnitude of annual–mean $APM_{2.5}$ concentrations across India, with greatest concentrations over the Indo–Gangetic Plain (Figure 2). The model slightly underestimates observed $APM_{2.5}$ concentrations (NMBF = –0.12 and NMAEF = 0.39). Our previous work used a similar model configuration and similarly underestimated measured $APM_{2.5}$ concentrations (Conibear et al 2018a). Overall, the simulated $APM_{2.5}$ concentrations show adequate skill to address questions of relative change in long–term $APM_{2.5}$ concentrations over India.

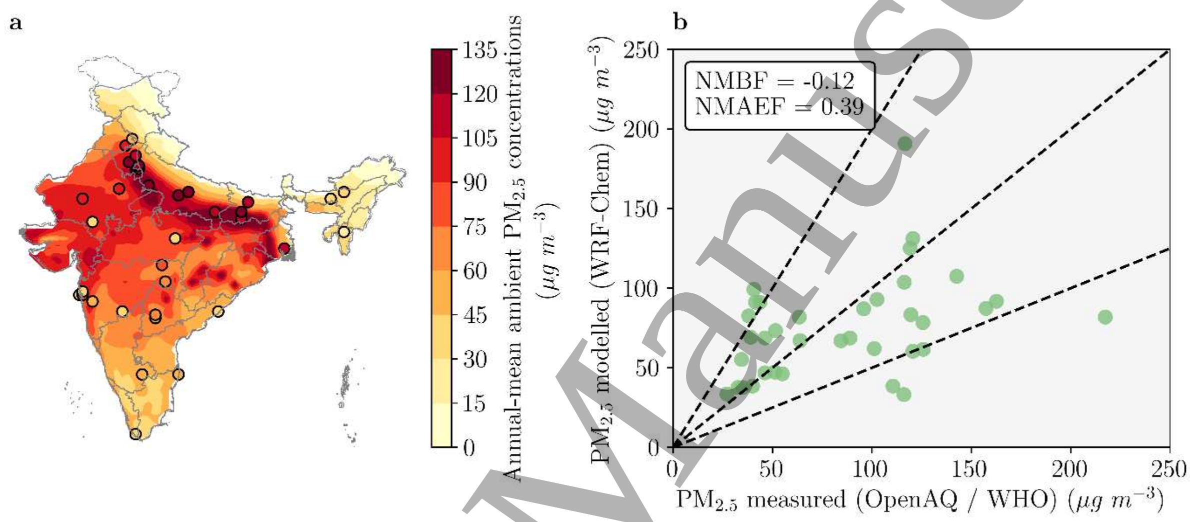


**Figure 2:** Evaluation of simulated (WRF–Chem; BASELINE emissions) ambient fine particulate matter ($APM_{2.5}$) against measurements from OpenAQ (OpenAQ 2019) and the World Health Organization (2018). (a) Simulated (background) and measurements (circles) annual–mean $APM_{2.5}$ concentrations. (b) Simulated versus measured annual–mean $APM_{2.5}$ concentrations. Normalised mean bias factor (NMBF) = –0.12 and normalised mean absolute error factor (NMAEF) = 0.39.

## 2.4. Health impact assessment

All the health impact assessments were for the same year (2015) to remove confounding influences of changing population size, population age, and baseline mortality rates. The health impact assessment diagnosed the disease burden attributable to $PM_{2.5}$ exposure using population attributable fractions (PAF) of relative risk (RR) from associational epidemiology. Intervention–driven variations in exposure were used to predict associated variations in outcome. This study followed the approach of the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2017 (GBD 2017 Risk Factor Collaborators 2018). The GBD2017 apportioned the disease burden attributable to $TPM_{2.5}$ between $APM_{2.5}$ and $HPM_{2.5}$ for solid fuel users and non–solid fuel users following relationships in Supplementary Table 2. The proportional PAF allowed for the individual disease burdens to be additive, due to the joint effects of $APM_{2.5}$ and $HPM_{2.5}$ being considered on single integrated exposure–response (IER) function per disease. The primary metrics used in the health impact assessment are the annual number of premature mortalities (MORT) and the rate of DALYs per 100,000 population, i.e. the total loss of healthy life. Detailed information on the methodology for the health impact assessment for $APM_{2.5}$ and $HPM_{2.5}$ are in the Supplementary Methods, where Supplementary

Figure 1 shows the $HPM_{2.5}$ concentrations and Supplementary Figure 2 shows the IER. The epidemiological data underlying health impact assessments are rapidly developing and a range of uncertainties remain (see Supplementary Methods). Recent developments to the IER for GBD2017 allow a better understanding of the combined impacts of household and ambient $PM_{2.5}$ exposure. As the main results of this paper are comparative, future epidemiological developments that influence the absolute disease burdens will not impact the comparative lessons drawn from this paper.

## 3. Results and Discussion

### 3.1. Current disease burden associated with $PM_{2.5}$ exposure in India

This study calculated annual–mean population–weighted $APM_{2.5}$ concentrations of 75.4 μg $m^{-3}$. This estimate is lower than the annual–mean measured $APM_{2.5}$ concentrations (90 μg $m^{-3}$, Figure 2b) and the latest GBD (91 μg $m^{-3}$, GBD 2017 Risk Factor Collaborators 2018), and higher than Chowdhury et al (2019b) (55 μg $m^{-3}$) (Supplementary Figure 3). This study estimated annual–mean population–weighted $HPM_{2.5}$, based on data from Shupler et al (2018), of 248.6 μg $m^{-3}$, 178.9 μg $m^{-3}$, and 216.2 μg $m^{-3}$ for females, males, and children, respectively.

Figure 3 shows the disease burden associated with $TPM_{2.5}$ exposure under the BASELINE scenario. This study estimated 1,190,000 (95UI: 764,000–1,601,000) premature mortalities per year associated with $TPM_{2.5}$ exposure, with 44% from $APM_{2.5}$ exposure and 56% from $HPM_{2.5}$ exposure. The DALYs rate associated with $TPM_{2.5}$ exposure was 2,900 (95UI: 1,900–3,900) per 100,000 population, with 45% from $APM_{2.5}$ exposure and 55% from $HPM_{2.5}$ exposure. The individual disease burdens associated with $APM_{2.5}$ and $HPM_{2.5}$ exposure are shown in Supplementary Figures 4 and 5, respectively.

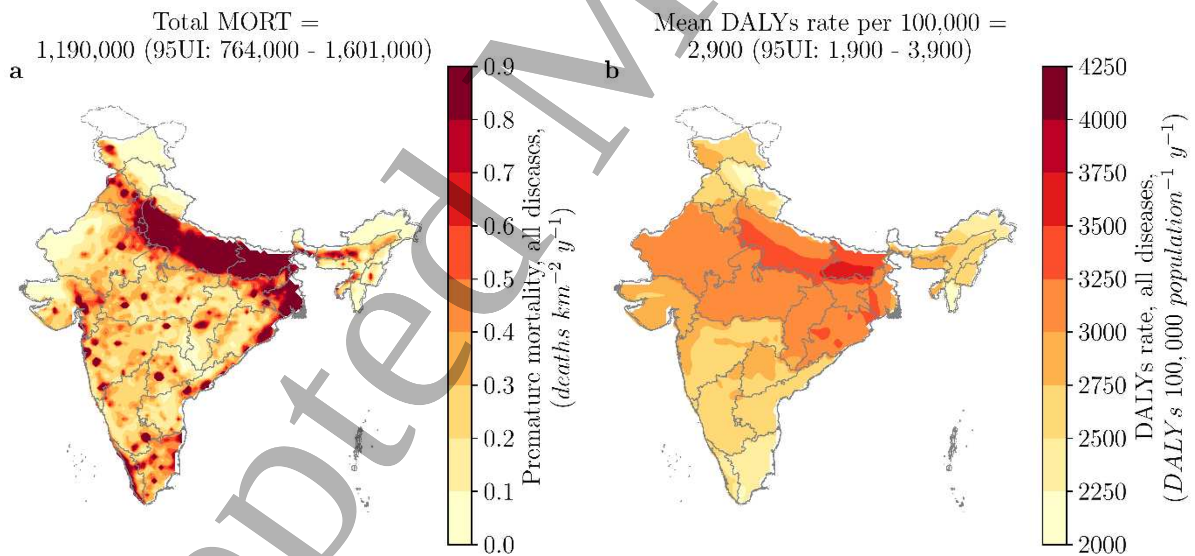


**Figure 3:** Disease burden associated with total fine particulate matter ($TPM_{2.5}$) exposure in India from the BASELINE. (a) Premature mortalities (MORT) and (b) rate of disability–adjusted life years (DALYs) per 100,000 population.

This study's estimates for the disease burden associated with $TPM_{2.5}$ exposure are slightly larger (+5% for MORT) those from the GBD2017 (Institute for Health Metrics and Evaluation 2019). This is the result of this study's larger estimated disease burdens associated with $HPM_{2.5}$ exposure (+31% for MORT), and smaller estimates of disease burdens associated with $APM_{2.5}$ (–17% for MORT). This study's larger disease burden estimates associated with $HPM_{2.5}$

exposure are due to this study's use of higher $HPM_{2.5}$ exposures and the state–specific solid fuel use, both with higher estimates in the densely populated Indo–Gangetic Plain. Overall, this study's disease burden estimates associated with $PM_{2.5}$ exposure in India are in general agreement with those from the GBD2017.

The health impact assessment was also estimated for ambient ozone ($O_3$) exposure, following the methodology of the GBD2017 (Supplementary Figure 6 and Supplementary Methods). The model underestimated $O_3$ concentrations (NMBF = –0.40 and NMAEF = 0.49), though the magnitude of the bias is similar to many regional modelling studies over India (Supplementary Figure 7 and Supplementary Methods). This study found no difference between the disease burden estimates across the five scenarios. Hence, this study focuses on the public health impacts associated with $TPM_{2.5}$ exposure.

### 3.2. Public health benefits of clean household energy

A complete transition to clean household energy (i.e. ALLLPG relative to BASELINE) reduced $APM_{2.5}$ concentrations by 25% (population–weighted from 75.4 μg $m^{-3}$ to 56.4 μg $m^{-3}$, annual–mean) as shown in Figure 4a. Improvements in air quality occur across India, with the largest reductions in pollution across the Indo–Gangetic Plain. The 25% reduction in $APM_{2.5}$ concentrations found here is similar to the 24% reduction estimated by the GBD MAPS Working Group (2018) with similar emissions. Previous studies estimated that a complete removal of residential emissions, without any replacement fuel, would lead to a 22–56% reduction in $APM_{2.5}$ concentrations (Chowdhury et al 2019a, Conibear et al 2018, Lelieveld et al 2015, Guo et al 2018, GBD MAPS Working Group 2018, Reddington et al 2019, Butt et al 2016, Gao et al 2018, Silva et al 2016, Karagulian et al 2017, Chafe et al 2014, Upadhyay et al 2018).

This study estimates that a complete transition to clean household energy would prevent 29% of the present–day disease burden associated with $PM_{2.5}$ exposure, preventing 348,000 (95UI: 284,000–373,000) premature mortalities each year (Figure 4). A complete transition to LPG reduces DALYs by 800 (95UI: 600–900) per 100,000 population.

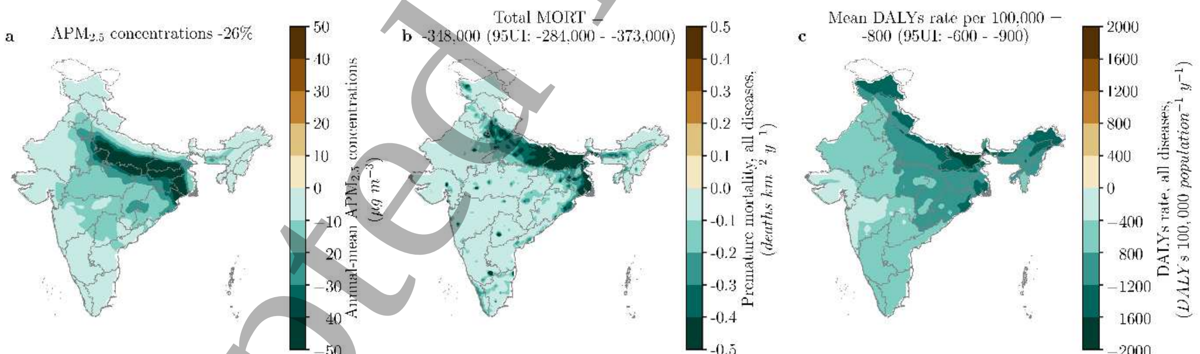


**Figure 4:** The impact of clean household energy on air quality and public health in India. (a) Annual–mean ambient fine particulate matter ($APM_{2.5}$) concentrations from the ALLLPG minus BASELINE scenario. The difference in the disease burden from the ALLLPG scenario relative to the BASELINE associated with the change in total fine particulate matter ($TPM_{2.5}$) exposure in India. (b) Premature mortalities (MORT) and (c) rate of disability–adjusted life years (DALYs) per 100,000 population. Negative numbers indicate a reduction in disease burden.

Chowdhury et al (2019b) found a complete transition to household LPG in India could reduce the number of premature mortalities associated with $APM_{2.5}$ exposure by 13%, where the population–weighted $APM_{2.5}$ concentrations reduced by 31% to 38 μg $m^{-3}$. This study finds that a complete transition to clean household energy can reduce the disease burden associated with $TPM_{2.5}$ by 29%, when the population–weighted $APM_{2.5}$ concentrations reduce by 25% to 56.4 μg $m^{-3}$. A key finding of Chowdhury et al (2019b) is that a transition to clean household energy would allow India to meet the National Ambient Air Quality Standard of 40 μg $m^{-3}$. While this study found a similar percentage reduction in $APM_{2.5}$ concentrations, annual–mean $APM_{2.5}$ concentrations in India remained above the National Ambient Air Quality Standard in this study due to higher baseline population–weighted $APM_{2.5}$ concentrations (75.4 μg $m^{-3}$ relative to 55 μg $m^{-3}$). The key novelties of this study are the consideration of $TPM_{2.5}$ exposure to account for the joint risks between $APM_{2.5}$ and $HPM_{2.5}$ exposure, and the use of a high spatial resolution (1 km) residential emission inventory based on village surveys of energy services required. As this study accounts for $TPM_{2.5}$ exposure, the disease burden estimates associated with $APM_{2.5}$ exposure are not directly comparable to those from Chowdhury et al (2019b). Despite these differences, this study confirms the major findings of Chowdhury et al (2019b), namely that a complete transition to clean household energy can substantially improve public health in India.

### 3.3. Incomplete transition to clean household energy

Table 2 and Figure 5 summarise the impacts of different household energy scenarios on air quality and public health at the national scale in India. Detailed data per state are provided in the Supplementary Data.

An incomplete transition to clean household energy might be limited by spatial access to LPG distribution (i.e. URB15 relative to ALLLPG). This transition, which reaches 80% of the population, nevertheless reduces the potential health benefits of a clean fuel transition by about 50%. Under this scenario, $APM_{2.5}$ concentrations are reduced by 12%, in contrast to the 25% reduction in the complete transition. This incomplete transition to clean household fuels results in a 13% reduction in total premature mortality, compared to a 29% reduction in the complete transition to clean fuels. Spatial constraints on access to LPG, falling under the category of "distribution potential" (Lam et al 2019), therefore reduce the avoided premature mortalities by 197,000 (95UI: 160,000–211,000) per year. This scenario also reduces the avoided DALYs by 600 (95UI: 400–600) per 100,000 population (Supplementary Figure 9).

If emission reductions are spread evenly among remote rural areas compared with urban centres (i.e. STATE50 relative to URB15), the national–mean $APM_{2.5}$ concentrations are also reduced by 12%. The spatial distribution of emission reductions means that $APM_{2.5}$ concentrations under STATE50 are larger in urban areas (up to +15 μg $m^{-3}$ in Delhi) and smaller in rural areas (up to –15 μg $m^{-3}$ in Uttar Pradesh and Bihar) relative to URB15 (Supplementary Figure 10a). The disease burden from $TPM_{2.5}$ exposure under STATE50 increases by 5% relative to URB15, and the number of premature mortalities increases by 55,000 (95UI: 41,000–62,000) per year (Supplementary Figure 10b). This increase is the net of two opposing changes: a 45% increase in the disease burden from $HPM_{2.5}$ exposure under STATE50 relative to URB15, because all households using solid fuels under the BASELINE retain some solid fuel use in STATE50, and a 15% decrease in the disease burden from $APM_{2.5}$ exposure caused by reduced emissions in high–population urban areas. The dominating role of $HPM_{2.5}$ is due to the proportional PAF and the non–linear IER, where large $HPM_{2.5}$ exposures under STATE50 drive large disease burdens from $TPM_{2.5}$ exposure. Comparing STATE50 to ALLLPG, where remote rural areas have relatively small emission reductions, the health benefits of the clean fuel transition are reduced by approximately 75%. The implication here is that in addition to reaching remote rural areas, the reductions in $HPM_{2.5}$ exposure need to be substantial.

Stove stacking with solid fuels (i.e. EMIS50 relative to ALLLPG) reduces the public health benefits of a clean fuel transition by approximately 75%. Under the stove stacking scenario,

$APM_{2.5}$ concentrations are reduced by 13%, compared to 25% in the complete transition. Stove stacking reduces the number of avoided premature mortalities by 255,000 (95UI: 201,000–278,000), and reduces the avoided DALYs by 600 (95UI: 500–700) per 100,000 population (Supplementary Figure 11). The implication of these constraints, coupled to the non–linear IER where risk decreases substantially at the lowest $TPM_{2.5}$ concentrations, suggests that large public health benefits are possible, but only if there is a nearly complete and exclusive transition to clean household energy.

**Table 2:** The impacts of clean household energy on air quality and public health in India. Total primary fine particulate matter ($PM_{2.5}$) emissions per year (Mt $yr^{-1}$). Annual–mean, population–weighted, concentrations from ambient fine particulate matter ($APM_{2.5}$) and household fine particulate matter ($HPM_{2.5}$). Disease burden estimates for premature mortalities (MORT, annual–sum) and rate of disability–adjusted life years (DALYs, annual–mean) per 100,000 population for $PM_{2.5}$ pollution ($APM_{2.5}$, $HPM_{2.5}$, and $TPM_{2.5}$). Results per scenario of BASELINE, ALLLPG, URB15, STATE50, and EMIS50. Values in parentheses represent the 95% uncertainty intervals.

| | **Scenario** | **BASELINE** | **ALLLPG** | **URB15** | **STATE50** | **EMIS50** |
|---|---|---|---|---|---|---|
| **Total primary $PM_{2.5}$ emissions (Mt $yr^{-1}$)** | | 8.8 | 4.9 | 6.9 | 6.9 | 6.9 |
| **$APM_{2.5}$ ($\mu g\ m^{-3}$)** | | 75.4 | 56.4 | 66.3 | 66.4 | 65.9 |
| **$HPM_{2.5}$ ($\mu g\ m^{-3}$)** | **Female** | 248.6 | 0.0 | 129.6 | 140.8 | 136.3 |
| | **Male** | 178.9 | 0.0 | 93.3 | 101.3 | 98.1 |
| | **Child** | 216.2 | 0.0 | 112.8 | 122.5 | 118.5 |
| **$APM_{2.5}$** | **MORT** | 522,000 (327,000–716,000) | 842,000 (481,000–1,228,000) | 686,000 (408,000–974,000) | 584,000 (356,000–813,000) | 570,000 (349,000–790,000) |
| | **DALYs rate per 100,000** | 1,300 (800–1,800) | 2,100 (1,200–3,100) | 1,600 (1,000–2,200) | 1,500 (900–2,100) | 1,400 (900–2,000) |
| **$HPM_{2.5}$** | **MORT** | 668,000 (438,000–885,000) | 0 (0–0) | 352,000 (232,000–465,000) | 510,000 (325,000–689,000) | 527,000 (332,000–716,000) |
| | **DALYs rate per 100,000** | 1,600 (1,000–2,100) | 0 (0–0) | 1,100 (700–1,500) | 1,200 (800–1,700) | 1,200 (800–1,700) |
| **$TPM_{2.5}$** | **MORT** | 1,190,000 (764,000–1,601,000) | 842,000 (481,000–1,228,000) | 1,038,000 (640,000–1,440,000) | 1,094,000 (681,000–1,502,000) | 1,097,000 (681,000–1,506,000) |
| | **DALYs rate per 100,000** | 2,900 (1,900–3,900) | 2,100 (1,200–3,100) | 2,600 (1,700–3,700) | 2,700 (1,700–3,700) | 2,700 (1,700–3,700) |

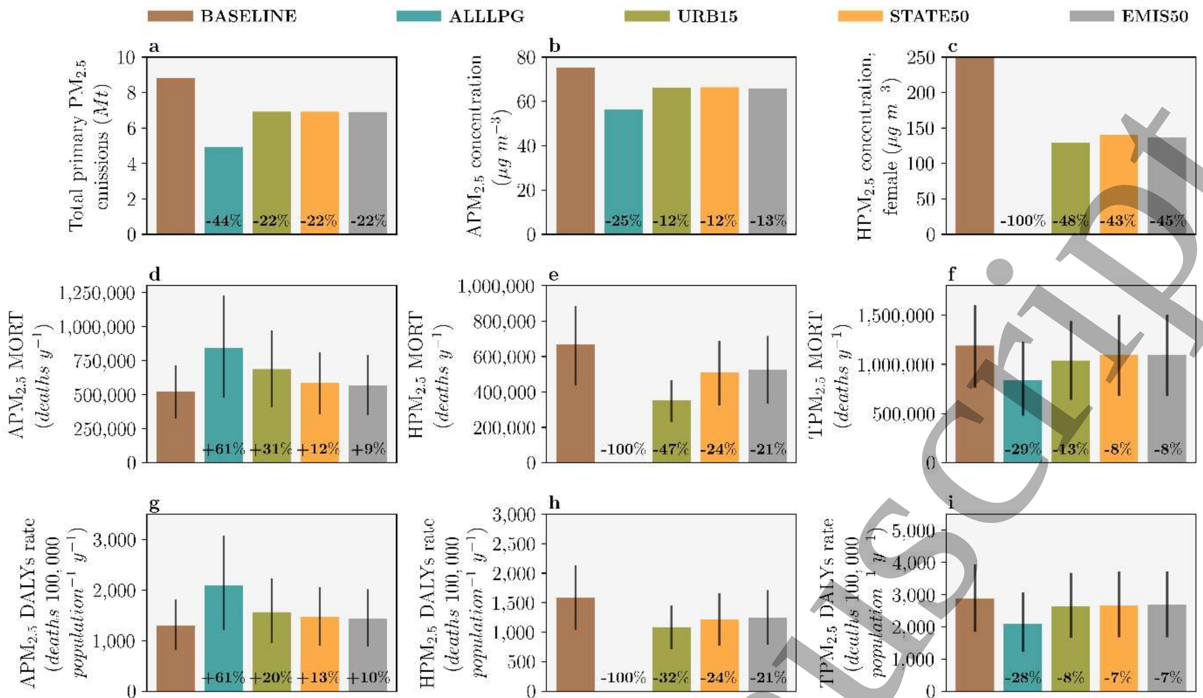


**Figure 5:** The impacts of clean household energy on air quality and public health in India. (a) Total primary fine particulate matter ($PM_{2.5}$) emissions (Mt). (b) Annual–mean, population–weighted, ambient fine particulate matter ($APM_{2.5}$) concentrations. (c) Annual–mean, population–weighted, household fine particulate matter ($HPM_{2.5}$) concentrations for females (similar reductions for males and children). (d–f) Annual–sum of premature mortality (MORT) associated with $APM_{2.5}$, $HPM_{2.5}$, and total $PM_{2.5}$ ($TPM_{2.5}$) exposure, respectively. (g–i) Annual–mean rate of disability–adjusted life years (DALYs) per 100,000 population associated with $APM_{2.5}$, $HPM_{2.5}$, and $TPM_{2.5}$ exposure, respectively. Results from the BASELINE and the ALLLPG, URB15, STATE50, and EMIS50 scenarios with the percentage change relative to the BASELINE. Error bars on disease burdens represent the 95% uncertainty intervals.

A key implication of these results is that it is critical for air pollution studies of residential emissions to consider the disease burden attributed to $TPM_{2.5}$ exposure, and not only the portion of $TPM_{2.5}$ attributed to either $APM_{2.5}$ or $HPM_{2.5}$ exposure. This is important because the exposure–outcome associations are non–linear and the joint effects of $APM_{2.5}$ and $HPM_{2.5}$ are proportional. This means that as the disease burden attributed to $HPM_{2.5}$ exposure decreases, the disease burden attributed to $APM_{2.5}$ exposure can increase, and vice versa. For example, under the BASELINE scenario 522,000 (95UI: 327,000–716,000) premature mortalities were attributed to $APM_{2.5}$ exposure, while under the ALLLPG scenario this attribution increased to 842,000 (95UI: 481,000–1,228,000) premature mortalities, despite a 25% reduction in $APM_{2.5}$ exposure. This increased attribution to $APM_{2.5}$ exposure when $HPM_{2.5}$ exposure is removed is due to the non–linear exposure–outcome association, where both $APM_{2.5}$ and $HPM_{2.5}$ exposures are individually high enough so that the RR is in the flatter section of the response (Supplementary Figure 2). Hence, a slightly lower total risk from $TPM_{2.5}$ exposure is now entirely attributed to $APM_{2.5}$ exposure, rather than being attributed approximately evenly between $APM_{2.5}$ and $HPM_{2.5}$ exposures. The importance of these joint effects are also demonstrated by the variation in frequency distributions between the URB15, STATE50, and EMIS50 scenarios (Supplementary Figure 8). All three scenarios have similar frequency distributions of $APM_{2.5}$ exposure (Supplementary Figure 8a), however, they vary in $HPM_{2.5}$ exposures (Supplementary Figure 8b) which drives variations in the overall disease burden associated with $TPM_{2.5}$ exposure (Supplementary Figure 8f), and the corresponding attribution between $APM_{2.5}$ and $HPM_{2.5}$ exposure (Supplementary Figure 8d and 8e). The importance of integrating $APM_{2.5}$ and $HPM_{2.5}$ exposures in India and other areas of high residential solid fuel use has been emphasised in previous studies (Balakrishnan et al 2014, Aunan et al 2018). High residential solid fuel use leads to large $HPM_{2.5}$ exposures and substantial source contributions to $APM_{2.5}$ exposures, whereby the reduction of residential emissions is an important equity issue in India (Cowling et al 2014, Kathuria and Khan 2007).

### 3.4. The importance of a complete transition to clean household energy

This study showed that the transition to clean household energy has the potential to reduce the disease burden associated with $PM_{2.5}$ exposure by 29%, preventing 348,000 (95UI: 284,000–373,000) premature mortalities every year. These potential public health benefits are dependent on the complete transition to clean fuels. This study demonstrated that the limited spatial access to LPG reduced health benefits by 50%, corresponding to a distribution potential for reduction benefits, and limited usage by 50% stove stacking with solid fuels reduced health benefits by 75%. This dependency of public health benefits on a complete transition to clean fuels has been seen in India (Smith 2017a, Pillarisetti et al 2014, 2018, Aung et al 2018, Hanna et al 2016).

To complete the transition to clean household energy and provide these substantial public health benefits, remaining access and usage issues need to be overcome (Tripathi and Sagar 2019, Kar et al 2019, Pattanayak et al 2019, Harish and Smith 2019, Gould and Urpelainen 2018). These include extending access to all, especially the most remote, poor, and vulnerable (Harish and Smith 2019), increasing refill rates (Pillarisetti et al 2019, Jain et al 2018), improving continual affordability (Harish and Smith 2019, Tripathi and Sagar 2019), and improving awareness of the need for continual use of clean fuels (Smith 2018, Harish and Smith 2019). The complete transition to clean household energy may also provide multiple benefits to sustainable development, human wellbeing, the climate, ecosystems, and the economy (Smith and Haigler 2008, Venkataraman et al 2010, Wilkinson et al 2009, Smith et al 2014, Bailis et al 2015, World Health Organization 2016, Rosenthal et al 2018).

We explored how hypothetical transitions to clean household energy could change air pollution exposure and the consequent change in associated health outcomes. We did not attempt to evaluate the impact of specific clean energy programmes. The isolated impacts of exposure change were quantified in a semi–equilibrium health impact assessment, holding demographics and background mortality rates constant. To directly assess accountability of the effectiveness of these specific air quality policies to improve human health, causal epidemiology study designs will be required once the policies are complete and the appropriate data is available (Zigler and Dominici 2014, van Erp et al 2012, Boogaard et al 2017, Burns et al 2019, Zigler et al 2016). Exposure–outcome differentials and effect modification among equity groups are important future research topics for air pollution studies in India.

## 4. Conclusion

We quantified the impacts of a nationwide transition from household solid fuel to LPG in India on the total loss of healthy life. We used WRF–Chem simulations to estimate that the transition to clean household energy would reduce ambient $PM_{2.5}$ concentrations by 25%. Reduced total $PM_{2.5}$ (ambient and household) exposure results in an estimated 29% reduction in the loss of healthy life, preventing 348,000 (95UI: 284,000–373,000) premature mortalities every year. These health benefits are contingent on a complete transition to LPG. If access to LPG is restricted to within 15 km of urban centres, corresponding to 80% of the national population, then the health benefits of the clean fuel transition are reduced by 50%. If half of original solid fuel users continue to use solid fuels in addition to LPG, health benefits of the clean fuel transition are reduced by 75%. As the exposure–outcome associations are non–linear, it is critical for air pollution studies of residential emissions to consider both ambient and household

$PM_{2.5}$ exposures. Our work shows that a transition to clean household energy can substantially improve public health in India, but the large public health benefits are dependent on reaching a complete transition to clean household fuels.

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## Contributions

LC, DVS, SRA, EWB, and TCB designed the research. KT and CV provided disaggregated emissions from the Global Burden of Disease from Major Air Pollution Sources project and the shapefile for India. TCB and NL provided residential emissions. CK provided WRFotron, a tool to automatize WRF–Chem runs with re–initialised meteorology. LC pre–processed model inputs, setup the model, performed the model simulations, performed the model evaluation, derived the exposure–outcome functions, conducted the data analysis and interpretation, created the figures, and wrote the manuscript. All authors commented on the manuscript.

## Data availability

Air pollution and health impact assessment data per Indian state that support the findings of this study are included in the Supplementary Data for this article. Code to setup and run WRF–Chem (using WRFotron version 2.0) is available through Conibear and Knote (2020). Further data that support the findings of this study are available upon request from the authors.

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